Vehicle to vehicle energy exchange in smart grid applications

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I. INTRODUCTION

There is an overwhelming consensus that the climate is changing in the Earth [1]. Governments around the world are adapting different policies to reduce pollution emissions, trying to mitigate their effects over the climate [2]. In Europe, EU has committed to cut its emissions of greenhouse gases (GHG) to 20% below 1990 levels [3], 40 % by 2030 [4] and 80-95% for 2050 [5].

The transport sector in Europe is the fastest growing consumer of energy and producer of GHG [6], therefore, electrification of the road transport is a key aspect to achieve these objectives and a way to reduce the EU's dependency on primary energy sources. European countries are promoting different initiatives to replace internal combustion engine (ICE) vehicles with EVs [7], [8]. These include fiscal incentives, plans for deployment of charging infrastructure, funding for research in new technologies and information.

This transition from ICE to a large penetration of EVs will have a great impact on the electric system, increasing requiring more electric generation to cover the peak demand and generating network congestion problems and voltage drops, particularly on the low voltage distribution grid for dumb charging schemes [9], [10].

The main barrier to EVs deployment is their reduced range. Even when the average daily distance in EU is around 70 km [11], which is allowable by almost all types of EVs in the market, this factor prevent potential customers from choosing an EV.

Other important mobility factor to highlight is that conventional ICE cars are parked, on average, more than 80% of the day [12]. If this mobility is done by EVs, they can be used as distributed storage in two ways: as controllable charges that absorb energy and proving energy back to the grid. This concept is commonly known as Vehicle to Grid (V2G) [13-15].

This paper presents a novel vehicle to vehicle energy exchange (V2VEE) between electric vehicles for reducing the impact on the electric grid.

Firstly, the mobility pattern of Flanders region (Belgium) is simulated using an agent based model called FEATHERS [16]. Assuming that all vehicles are full charged during the night period, when the electric variable tariff is the lowest, and fixing an average electric consumption per km for all EVs, two main set of users will be identified: those drivers who can perform all daily trips with excess energy in their batteries at the final of the day, and other set of drivers who can perform all their daily trips, but intermediate charging is required during their daily scheduled stops.

Taking the advantage that vehicles from both sets can coincide in the same area at the same time period during the day, it is possible to transfer energy from one vehicle to the other, avoiding buying energy directly from the electric grid, and reducing significantly the impact of the charging process during the day.

The organization of the paper is as follows: Section II defines the activity based mobility model and determinates the number of EVs for both sets. Section III presents the optimization algorithm to be used for minimize the electricity cost of charging during the day. In Section IV a novel V2VEE market is defined and the benefits of this scheme is analyzed in Section V. Finally, conclusions and future work are presented in Section VI.

II. ACTIVITY BASED MODEL

The temporal and spatial behavior of EVs is modeled using an activity-based (AB) micro-simulation model that predicts the daily scheduled activities for each member of a synthetic population, called FEATHERS. FEATHERS is an AB model [1] based on real travel behavior OVG surveys in Flanders region (Belgium). The information of these surveys let synthesizing for each member of the population when, where and which activities are done and the transportation mode used (by foot, by train, by car, etc.). For that, Flanders region is divided in 2368 different traffic analysis zones (TAZ) with an average area of 5.5 km2 per zone (Fig. 1) and a complete schedule list for the whole population is obtained. Once drivers are identified among entire population, different EVs penetration rates can be assumed and the energy demanded by these EVs in each TAZ due to the mobility needs can be evaluated.

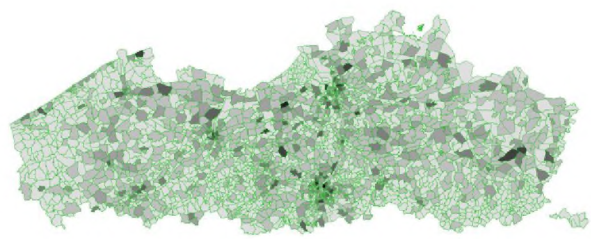

Fig. 1. FEATHERS Flanders region meshed in TAZs

According to FEATHERS model, there are 1,141,735 vehicles driving daily around the Flemish region. An average consumption of 0.179 kWh/km is assumed, as in [17], obtaining three different sets of vehicles: Set A is composed by vehicles that do not require intermediate charging to complete their daily activity schedule (926,983 EVs, 81.18% of them). Set B represents those vehicles that can finish their daily schedules without any mobility behavioral changes, performing an intermediate recharging. This charging will be done while the car is stopped and its owner is performing a particular activity (123,580 EVs, 10.8% of them). Finally, set C is composed by those vehicles which are not able to finish their daily schedule without modifying it, since they require additional time for (possible fast) charging.

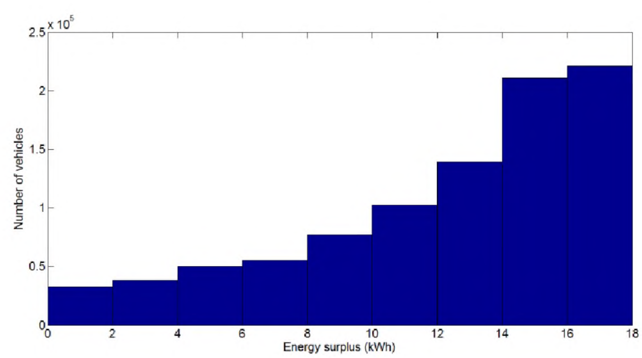

Fig. 2. Total energy surplus of selling vehicles (set A)

Fig. 2 shows the excess energy distribution of vehicles from set A, while Fig. 3 shows the demanded additional energy distribution of vehicles from set B (the last bar corresponds to vehicles requiring additional more than 27 kWh) for whole Flanders region. As it can be observed, there are more energy stored in the batteries of vehicles from set A than the total energy demanded by all vehicles from set B.

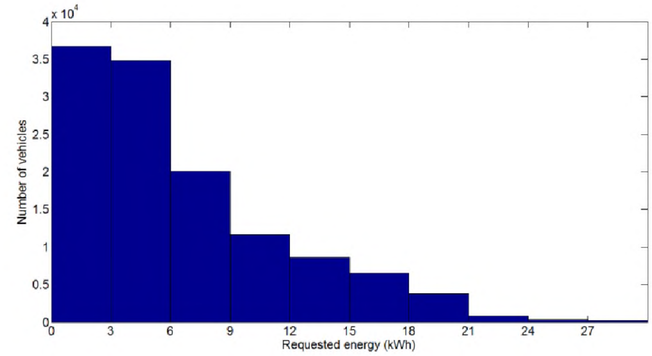

Fig. 3. Total energy demand of buying vehicles (from set B).

III. Charging Optimization Algorithm

Taking into account the scheduled activities of each agent provided by the FEATHERS model, it is observed that some agents are not able to complete all daily trips without recharging their vehicles before arriving home, assuming the batteries are completely full at the beginning of the day. Therefore, it is necessary to establish when and where they will recharge them optimizing the cost of this intermediate charging. Assuming the variable hourly price can be provided in advance to the vehicle owners by the electric market operator with sufficient accuracy, (as it is done by Belgian Power Exchange, Belpex [18]), agents will be able to optimize their charging schedule with their own mobility restrictions, so that they can fulfil their daily agenda without modifying their mobility behavior.

The charging optimization algorithm used is given by equations (1)-(5). It is explained in detail in [17].

$$\min\left[\sum_{t=T_{dep}}^{T_{arr}} cod(t)P_r(t)\right] \tag{1}$$

Subject to the following restrictions:

$$SoC_{\min} \leq SOC(t) \leq SOC_{\max} \tag{2}$$

$$0 \leq i(t) \leq CR \tag{3}$$

$$SOC(t) = SOC(t-1) + i(t) - o(t) \tag{4}$$

$$cod(t) = VCA(t)i(t)/\gamma_{eff} \tag{5}$$

Where variables and parameters are defined in Table 1. The objective function (1) minimizes the charging cost of the vehicle for the time period between its departure (with battery fully charged) and its arrival. Constraint (2) sets the limits for the battery state of charge (SOC) and constraint (3) represents the charging power limit. Equation (4) describes the battery charging and discharging processes. Charging efficiency (γ_{eff}) and vehicle charging availability (VCA) are considered at equation (5).

TABLE I. OPTIMIZATION MODEL VARIABLES AND PARAMETERS

Description	Symbol	Value	Unit
Energy hourly price	$Pr(t)$	$[Pr_t]$	€/kWh
Charging availability	VCA(t)	[0,1]	-
Charging Limit	CR	24	kWh
Discharged energy	o(t)	$[o_t]$	kWh
Charge efficiency rate	γ_{eff}	0.95	-
Minimum allowed SOC	SOC_{min}	5	%
Maximum allowed SOC	SOC_{max}	100	%
Initial SOC	SOC(0)	100	%
Charge energy to battery	i(t)	-	kWh
Charge energy from system	cod(t)	-	kWh

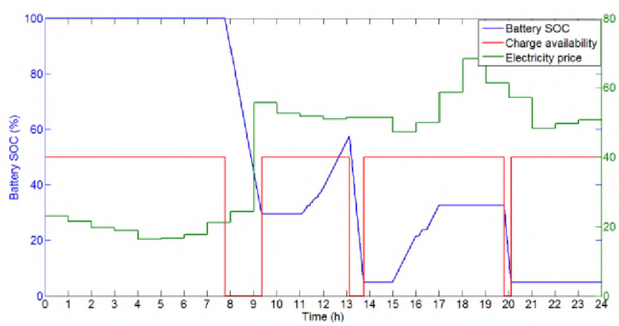

Fig. 4. Battery SOC evolution using charging optimization algorithm.

Fig. 4 shows the result of applying this optimization algorithm for a single vehicle. The agent carries out three trips: first one between 07:47 and 9:21 (88.71 km), the second one from 13:08 to 13:45 (66 km) and a last one from 19:48 to 20:06 (34.7 km). The total distance driven is 189 km, implying a consumption of 33.8 kWh, higher than battery capacity (limited to 24 kWh). The required charging is programmed to take place twice: The first charge occurs between 11:02 and 13:08, where the price is optimum within the first period in which the vehicle is parked. The vehicle is partially charged, since the energy price is lower within the next period in which the vehicle is parked. After the second trip, the vehicle performs the last charge between 15:00 and 17:00, filling the batteries with enough energy to finish its last trip. The SOC at the end of the day is the minimum allowed to the battery, since otherwise the vehicle would have recharged an unnecessary amount of energy. Charge availability is displayed in red.

IV. V2V ENERGY EXCHANGE

As it can be noticed from Fig. 2 and 3, it is possible to create a market so that the additional energy charged at night by vehicles from set A can be used by vehicles from set B during the day. This market will help to reduce the energy cost for the vehicle's owners and also contribute to reduce the impact of electric vehicles on the electric grid.

The market mechanism works as follows. Firstly, EVs from set B optimize their intermediate charging cost and program their energy requirements according to the expected grid price, which is facilitated by the electricity market operator.

Then, when these vehicles are parked in a particular TAZ, they demand the amount of energy scheduled. This energy can be provided by two different sources: directly from the electrical grid, at the current tariff price (green line on Fig. 4), or extracted from those vehicles of set A which are parked at the same TAZ at the same time period, but paying a different market price. This market application between vehicles is called vehicle-to-vehicle energy exchange (V2V EE).

EVs from set A will be denoted by EVAs and EVs from set B will be denoted by EVBs.

The objective of the V2V EE model is to minimize the cost of the energy employed by the EV fleet at every TAZ and every period of time. For this purpose some assumptions have been considered. Night charge takes place between 00:00-09:00h, during which all EVs are fully charged before starting their daily schedule. The minimum price at which the energy can be sold by EVAs is the maximum grid electricity price that they paid to be recharged at night, taking into account the losses in the charger. The maximum sold price considered by each particular EVAs is the grid electricity price at the current time. Finally, all EVAs offer, in each sales period, all their saleable available energy.

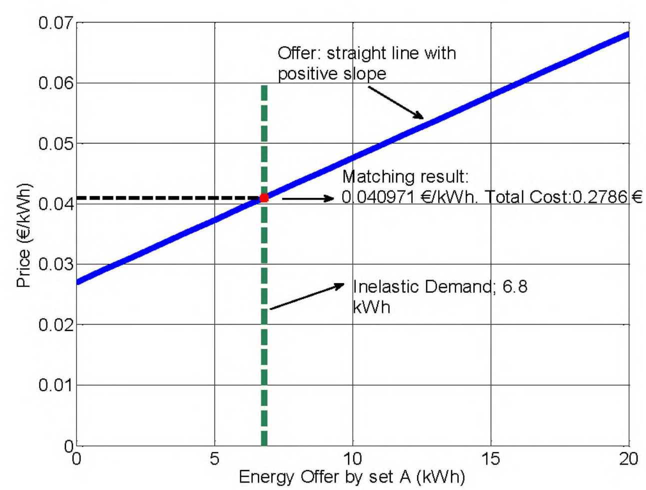

Fig. 5. TAZ price matching.

The demand model of each EVB is considered totally inelastic because their charging needs must be completely satisfied; that is, the demand does not depend on the given price. On the other hand, the offer model of each EVA is considered as a linear equation with positive slope such that the more energy is exchanged, the more expensive is sold (see Fig. 5 which depict both models). Therefore, the following equation defines the offer model:

$$p_i = \alpha_i x_i + p_{\min} \tag{6}$$

Where:

$$\alpha_i = \frac{(p_{\max} - p_{\min})}{xoff_i} \tag{7}$$

And p_i represents the price paid to EV number i from set A in €, x_i represents the energy deployed by the EV number i from set A in kWh, p_{max} represents the maximum price to be paid to EV number i from set A in €, p_{min} represents the minimum price to be paid to EV number i from set A in € and $xoff_i$ represents the energy offered by EV number i from set A in kWh.

Therefore, the energy exchanged unit cost equation that has to be minimized in each period and mobility zone is given by:

$$f(\mathbf{x}) = \sum_{i=1}^{n} \frac{p_i(x_i)x_i}{D} \tag{8}$$

With the following constraints:

$$g_k = x_k - E_{\max} \le 0, k = 1.n \tag{9}$$

$$g_{n+1} = \sum_{i=1}^{n} x_i - D = 0 \tag{10}$$

Where D is the total energy demanded by all EV from set B in a particular TAZ in kWh, n is the number of EVs from set A in this TAZ and E_{max} is the maximum energy deliverable by the charger. To solve this problem, Lagrange multipliers are applied to (8), obtaining the following system equations:

$$\frac{\partial f}{\partial x_i} = \sum_{k=1}^{n+1} \lambda_k \frac{\partial g_k}{\partial x_i}, \quad \forall i = 1,..,n \tag{11}$$

$$\lambda_k g_k = 0, \quad k = 1,..,n+1 \tag{12}$$

$$g_k - E_{\max} \le 0, \quad i = 1,.n \tag{13}$$

From (6) and (8):

$$\frac{\partial f}{\partial x_i} = \frac{2\alpha_i x_i + p_{\min}}{D}, \quad \forall i = 1,..,n \tag{14}$$

From (9):

$$\begin{aligned} \frac{\partial g_k}{\partial x_i} &= 1, \quad k = i \\ \frac{\partial g_k}{\partial x_i} &= 0, \quad k \ne i \end{aligned} \tag{15}$$

From (9) and (12):

$$\lambda_k = 0, \quad k = 1,.n \tag{16}$$

The following linear system is obtained from (10)-(16):

$$\begin{aligned} &\frac{2\alpha_i p_i + p_{\min}}{D} = \lambda_{n+1}, \quad \forall \mathrm{i} = 1,..,\mathrm{n} \\ &\sum_{\mathrm{i}=1}^{\mathrm{n}} x_i - D = 0 \end{aligned} \tag{17}$$

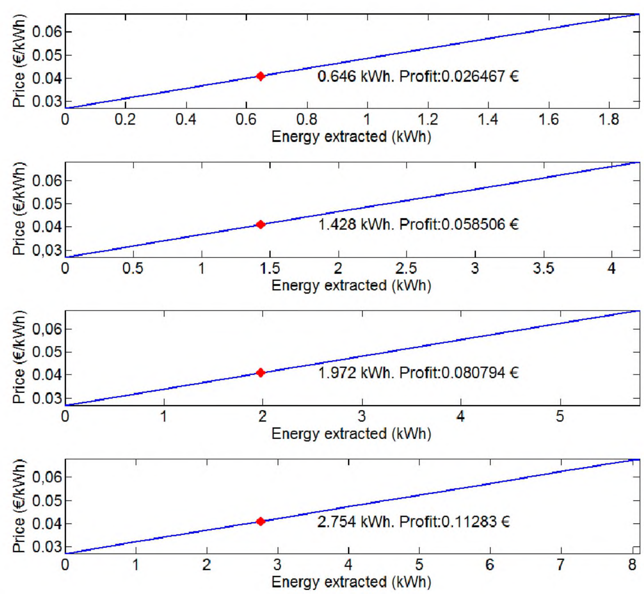

Fig. 6. TAZ price matching.

The result solving (17) for a certain TAZ and a certain time can be interpreted as the following: the amount of energy given by each individual EVA is directly proportional to the ratio between the amount of energy it offers and the energy offered by the whole EVAs at this moment. If a EVA has to transfer more energy than that corresponding to its limit, this energy is shared among the other EVs from the set A, until no EVA surpass their own energy output limit; if there is not enough vehicles or energy within them available, EVBs will need to take from the grid the remaining energy at grid price.

The market electricity price for all EVAs is the same in either case. Results of applying the market to a determined TAZ and period can be seen in the following section.

V. Results

Fig. 5 and Fig. 6 show a match V2V market for a particular TAZ and at a certain period. In this case, the minimum sold price is 0.027 €/kWh, the grid electricity price is 0.068 €/kWh and the maximum energy a vehicle can deploy is 3.3 kWh. At the zone under study, there are 4 available EVAs with 1.9, 4.2, 5.8 and 8.1 kWh of stored saleable energy and the energy demanded by the total EVBs is 6.8 kWh. As it can be seen, the demanded energy is given by the EVs proportionally to their offered energy, as commented before. The sold prices are the same for all EVs, 0.4097 €/kWh. The cost of this transaction has been 0.2786 €; if this energy had been deployed directly by the electric grid, the total cost would have been 0.4628 €.

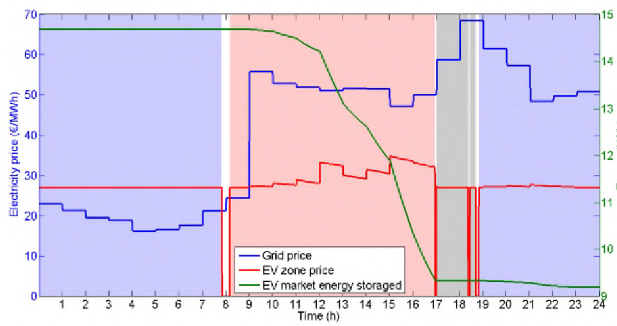

Fig. 7. Single EV from set A market perspective.

Fig. 7 shows the application of the V2V EE model from the perspective of a single vehicle from set A. The vehicle starts the day fully charged, but since it has been programmed to accomplish certain activities, it has available for the market a certain amount of energy, represented by the green line. The red line represents the price paid for the energy in the TAZ zone where the vehicle is placed. While the owner is driving this value is displayed as 0; if no energy is demanded the value is equal to the minimum price. The blue line represents the grid electricity price at the moment. The different areas in which the vehicle stays are represented in differently colored backgrounds, with white representing periods in which the vehicle moves.

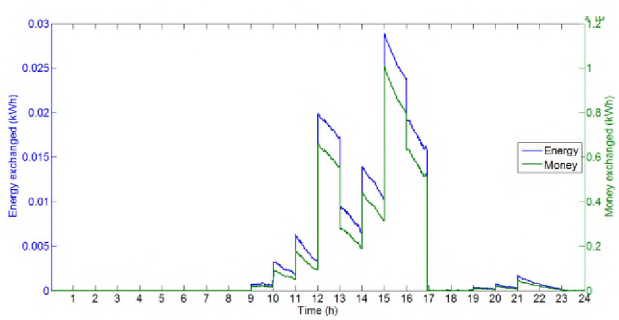

Fig. 8. Energy and money exchanged for a single EV from set A.

The energy flow and cost are represented in Fig. 8. As it can be seen, when the vehicle is traveling from one TAZ zone to other, the energy given by an EVA and its profit vary drastically. This happens because of the dependency between the market electricity price and the amount of vehicles requesting and offering energy at the same time. Since there is a relatively low limit in the amount of energy that can be offered by a single vehicle during a certain period of time, the energy price is mainly influenced by the relationship between the energy demanded from vehicles from set B and the power capacity of vehicles from set A, rather than the energy stored in their batteries.

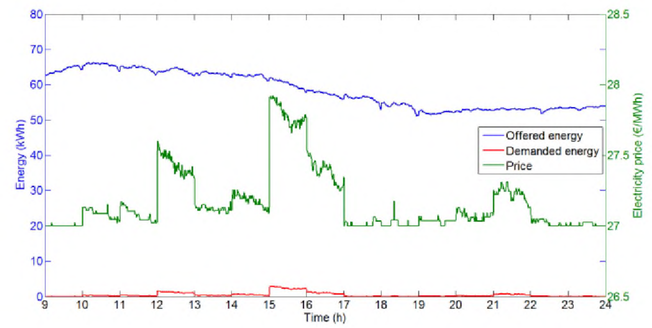

Fig. 9. Effect of market in zone with offer much higher than demand.

Fig. 9 shows the effect of the market for a zone in which the offer is much higher than the demand. Because of this, the price barely surpasses the minimum price along the day. The result is a low profit for the selling vehicles but cheapest prices for the buying vehicles. Note that the maximum price, obtained at 15:00, is lower than electricity grid price (see blue line Fig. 7 and note that the price axis have been interchanged in Fig. 7 and Fig. 9).

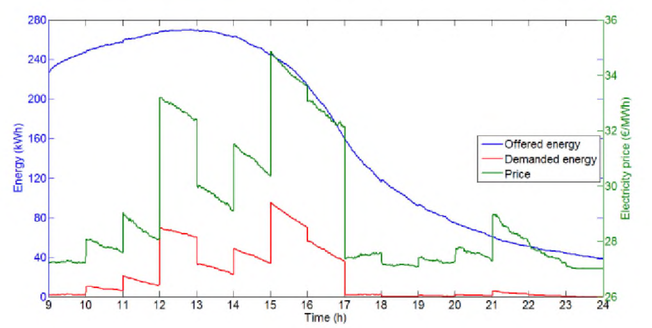

Fig. 10. Effect of market in zone with offer higher than demand.

Fig. 10 shows the effect of the market for a zone in which the offer is higher than the demand, although this difference is not as important as in the previous case. The importance of the ratio between buyer and sellers is marked in the resulting price at 11:00 (high offer - high demand) and at 21:00 (low offer ¬- low demand); the electricity grid price is similar in both cases: 51.72 and 48.29 €/MWh. Therefore, in this case the market results in a moderate profit for the selling vehicles and cheaper prices for the buying vehicles than that of the grid.

Finally, Fig. 11 shows the effect of the market for a zone in which the offer is similar to the demand, a case which is rare and frequently involving low numbers of both buying and selling vehicles. Consequently, the market results in high profits for the selling vehicles and prices similar to that of the grid, from which they may have to buy part of the energy if there is not enough sellers.

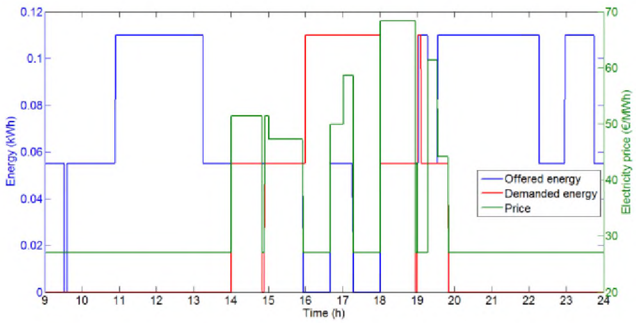

Fig. 11. Effect of market in zone with offer similar to the demand.

VI. CONCLUSIONS

Mobility data indicates that if EVs were used instead of ICE vehicles, around 80% of drivers, would have enough range to complete all trips that they need during the day, charging the EV only during the night while are at home (set A); and around 15% of drivers would complete all trips with additional charging while making their daily activities without any scheduled mobility modification (set B). In addition, it is observed that the energy available at the end of the day in EVs from set A is more than the needed for EVs in set B to making the daytime charges.

V2V EE model is presented as a path to diminish the impact on the electric system that EV charging would produce during the day. In addition, the V2V market can be applied locally or in a determined region, facilitating its integration in a smart grid environment.

In the V2V market model, the EVs optimize their day-ahead charges using the electric grid prices. Once the total EVs demand is programmed, the EVs that have, without need of charge during the day, extra energy after its last trip, take in advantage that surplus energy to offer it to the EVs that need to charge during the day at a price lower than the grid price.

Results show that lower energy prices are achieved through the application of this method. Prices are mostly dependent on the ratio between buying and selling vehicles, which is highly favorable for the last ones in most TAZs. Grid energy price influences mostly on the moment in which the vehicles charge, also establishing a maximum price for the energy exchange.

ACKNOWLEDGMENT

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement nº 270833.